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Processing Determinants of Reading Speed

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SUMMARY

Two groups of university undergraduates differing in reading ability were tested on a number of reaction-time tasks designed to determine the speed of encoding visual information at several different levels. In addition, the subjects were given tests of sensory functions, verbal and quantitative reasoning ability, short-term auditory memory span, and ability to comprehend spoken text.

The groups did not differ on the sensory tests. However, the faster reader group had faster reaction times on all of the reaction-time tasks, and the size of the fast-reader advantage increased with the mean reaction time. Faster readers also performed more accurately in verbal and quantitative reasoning, short-term auditory memory, and speech comprehension.

Regression analyses suggested that the ability to comprehend spoken material and speed of accessing overlearned memory codes for visually presented letters represented two important independent correlates of reading ability in our sample of subjects. Two variables reflecting these abilities—the percentage of correct answers to a listening comprehension test and the reaction time for correct responses in a letter-matching task—accounted for nearly all of the variance in reading ability tapped by both of our reading tests.

In a second experiment, no reaction-time difference was found between fast and average readers in a matching task requiring no long-term memory code access but considerable visual information processing as indexed by overall mean reaction time. The results supported the conclusion that one skill allowing fast readers to capture more information from each reading fixation is faster access to letter codes from print.

Effective reading requires the integrated use of many component processes, each process determining in part a person's proficiency. Unfortunately, for those who wish to analyze these processes, most educated adults read with enough ease and fluency to obscure this underlying complexity and hide these components within an apparently unitary act. However, recent advances in the study of human information processing provide some hope that an analysis of the components of the reading process, and of the processing determinants of individual differences in reading, is not beyond our grasp. The information-processing literature suggests a number of processing skills that may contribute to fluent reading ability, and previous research provides us with methods that may permit isolation of these processing skills in simplified task situations.

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One tack a research project might take in studying individual differences in reading would be to use the analytic techniques of componential analysis (Sternberg, 1977). These techniques make use of a serial stage model of the process under investigation, in which the parameters of the model can be interpreted directly as representations of the duration of each component stage contributing to overall task performance. Sternberg has had some success in applying this technique to the study of individual differences in analogical and syllogistic reasoning tasks. However, this approach seems unlikely to work with a process as complex and interactive as reading (McClelland & Jackson, 1978). While some authors have suggested that the components of the reading process are organized in a strictly linear, serial fashion (e.g., Gough, 1972; Mackworth, 1972), others, who have argued for overlapping, parallel-contingent stages of processing, have had more success accounting for several important findings (McClelland, 1976; Theios & Muise, Note 1). In a parallel-contingent processing system, the duration of a stage of processing is not a meaningful construct.

Even if we imagined that we could measure the rate or efficiency of a given component of the reading process, there are difficulties that make the estimation of these time parameters extremely difficult. First, many researchers have argued that some of the components of the reading process become automatic with practice (LaBerge & Samuels, 1974). Consistent with the general view that readers have a limited amount of processing resources that they can allocate to different components of reading (Norman & Bobrow, 1975; Rumelhart, 1978), automatization of one component would free resources for other, less automatic components (Gleitman & Rozin, 1973). Second, Rumelhart (1978) has recently argued that the results of processes involved in extracting syntactic and semantic structure feed back on processes concerned with the more literal aspects of reading such as feature, letter, and work identification. If so, the apparent duration or efficiency of one component of the reading process will depend on the rate and efficiency of all other components. In view of these difficulties, we have adopted the strategy of simplifying the task situation as much as possible to isolate potential component processes from the confounding effects of the other processes with which they are enmeshed within the integrated act of reading.

Some facts are already known about the determinants of reading rate. The earliest reading research (e.g., Javal, 1878; cf. Huey, 1968) showed that rate of reading is dependent on the number of eye fixations per unit of text. Faster readers make fewer fixations per line than slower readers but spend about the same amount of time per fixation. These facts suggest that faster readers may be able to process more text per reading fixation. An experiment by Gilbert (1959) supports this conclusion. Gilbert presented short sentences, under conditions simulating a single reading fixation, to readers of differing ability. Fast readers were able to report more of the contents of these displays than slow readers. Gilbert's finding suggests that we may be able to account for some component of individual differences in reading ability by isolating differences in component processes that operate on the input received during each fixation.

In a previous study (Jackson & McClelland, 1975), we considered some of these possible component processes in a variety of tasks. We found no difference in the performance of fast and average readers on tasks involving the perception of one element or two widely separated elements in which the limitation on performance was presumably of a sensory origin. Groups of fast and average readers had equivalent temporal resolution as indexed by the target exposure time required to identify a single letter under conditions of preexposure and postexposure patterned masking. Likewise, we found no fast reader advantage in parafoveal sensitivity as measured by the accuracy of reporting pairs of letters presented in the periphery.

When several display elements were presented, fast readers were able to report more of them correctly, even when there was no higher order structure present in the display. The largest difference between fast and average readers was obtained in a task like Gilbert's (1959) in which subjects attempted to report all of the words in a sentence that was presented briefly and followed by a patterned mask. However, a reliable difference was also obtained when subjects attempted to report all of the letters in a string of unrelated consonants presented under similar conditions (see also Loiseau, 1974). Furthermore, fast readers performed more accurately in a probe forced-choice test (Reicher, 1969) of the information extracted from sentences under these conditions. The procedure guaranteed that a difference in accuracy was not due to guessing from superior knowledge of linguistic structure in conjunction with contextual cues. Instead, the results demonstrated that faster readers were able to pick up more information.

One class of interpretations of these results might be based on sensory limitations. Although we previously tested for sensory differences between fast and slow readers, there is one possible sensory difference that we did not test. It is possible that fast readers were able to report the contents of a multielement display more accurately than slow readers because they were less sensitive to lateral masking at sensory levels of processing. Bouma (1973) has reported evidence of lateral masking, as have Eriksen and Rohrbach (1970) and Estes, Allmeyer, and Reder (1976). In the present study, we tested sensitivity to lateral masking by repeating the single letter threshold and peripheral span tasks of our earlier study, both with and without nonletter mask characters surrounding the target characters in the display.

It seems likely to us that individual differences in the ability to read depend more on central cognitive processes than on peripheral sensory processes. Therefore, we have focused our attention primarily on isolating central processes that could contribute both to effective reading and to the pickup of information from the contents of a single fixation.

What are some potential sources of individual differences in reading that are based on central processes? Of course, the answer to this question depends on one's theory of reading. A basic claim of many information-processing models of reading (e.g., Estes, 1975; LaBerge & Samuels, 1974; Massaro, 1975) is that reading depends on a hierarchical organization of subprocesses. In constructing a conceptual representation of the material read, it is often suggested that information is first analyzed for visual features and then passed successively to letter, word, semantic-syntactic, and conceptual levels of analysis. Several researchers have suggested a phonological encoding level prior to accessing word meanings (Rubenstein, Lewis, & Rubenstein, 1971; Rubenstein, Richter, & Kay, 1975), although the role of obligatory verbal coding in accessing the meaning of words is in doubt (Baron, 1973; Frederiksen & Kroll, 1976; Kleiman, 1975).

In the terms of this hierarchical framework, readers may differ in the efficiency of any or all of these component processes. Also, differences in many of the components could account for our earlier findings in tachistoscopic perception if we assume that information that travels through the hierarchy to deeper levels, before lower level information is disrupted by masking or dissipated by decay, will have a greater chance to become available for report (McClelland, 1976; Turvey, 1973). Thus, faster readers may be able to report more information from a single fixation because they can form the appropriate higher level representations more quickly, before lower level representations from which the higher ones derive are lost. Within the context of this view, the fact that fast readers reported more unrelated letters correctly than slower readers in our unrelated letter task suggests that the fast readers' advantage may begin as early as levels of processing concerned with feature extraction or letter identification.

In the present research, we looked for evidence concerning the speed of forming

	RESPONSE	
Task	Same	Different
simple pattern	+ +	□ +
letter		
physical	A A	–
name	A a	Br
synonym	ABRUPT SUDDEN	AGED STAY
homonym	BARE BEAR	RARE REAR

Figure 1. Examples of a same and different stimulus pair for each of the reaction-time matching tasks used in Experiment 1.

representations at different levels using a simultaneous matching procedure. To tap different levels of processing, we varied the stimulus elements and/or the basis for comparison across several different tasks. In each task, the visual display contained two simultaneously presented elements and subjects were required to respond as fast as possible whether the two were the same or different (see Figure 1 for examples). In one version of this task, the stimuli were letters, and subjects were required to respond "same" if the letters were either physically identical or identical in "name" as in the paradigm developed by Posner (e.g., Posner, Boies, Eichelman, & Taylor, 1969; Posner, Lewis, & Conrad, 1972). In another version, the display elements were words and subjects were required to respond same if the words were synonymous. In yet another version, the display elements were again words, but subjects were required to respond same if the words had the same sound (i.e., were homonymous). Thus, these tasks attempted to reflect the processes of forming visual letter codes, letter identity codes, semantic word codes and verbal (i.e., acoustic or articulatory) word codes.

The reaction times produced by these tasks include components other than those of primary interest. Individual differences between fast and average readers in any one task might well reflect general task requirements independent of the processing required to form a representation at the specific level required for the given task. To provide some indication of the magnitude of individual differences in any general processing requirements common to all simultaneous matching tasks, we created a very simple pattern matching task in which the subject was required to compare two very simple stimuli and to respond *same* if they were physically identical.

One possible source of individual differences in the matching tasks just described is the process of comparing the representations derived for the two display elements. This process of comparison is confounded with the process of forming the representations to be compared. Fortunately, it is possible to tap the process of comparison using a display search paradigm in conjunction with the standard Sternberg (1969) analysis of results obtained in both memory and display search. In our version of display search, adopted from Egeth, Jonides, and Wall (1972), subjects viewed a target letter, followed by a display containing two, four, or six letters, and they were required to indicate whether or not the target was present in the display. The magnitude of the increase in reaction time with display size is taken, following Sternberg's analysis, to reflect the rate of comparison of target and display characters. Thus, if faster readers differ from average readers in the rate of comparison, we would expect faster readers to show less of an increase in reaction time with display size than average readers.

Another potential source of individual differences in reading ability may lie in the capacity of verbal short-term store. Several researchers have found that verbal storage plays an important role in certain types of sentence processing tasks (Grey, 1975; Kleiman, 1975; Levy, 1975). Whether the comprehension processes required for fluent reading actually make use of short-term verbal store has not yet been determined. Perhaps it counts against this possibility that Perfetti and Goldman (1976) found no differences in short-term memory capacity for digits between groups of grade-school students differing in reading comprehension skill. On the other hand, Hunt, Lunneborg, and Lewis (1975), using college students, did find a relation between short-term memory capacity and verbal aptitude, and verbal aptitude is highly correlated with reading ability. Also, it is easy to see how a larger short-term storage buffer could be responsible for superior tachistoscopic report in our earlier study. To gain more direct evidence on the importance of individual differences in verbal short-term memory in determining individual differences in reading rate among adult readers, we tested the short-term memory capacity of fast and average readers using an auditory letter-span task analogous to the standard digit-span task. Letters were used to make the task more directly comparable to the visual letter-span task of our previous experiment.

Thus far, we have focused on a number of visual decoding processes that could potentially account for differences in reading performance and that could come into play within a single fixation. Although these processes may well be important determinants of reading performance, it seems obvious that a large measure of the variability in reading speed across subjects results from differences in general language comprehension skills. Further, as just noted, it seems likely that language comprehension depends on verbal aptitude—that is, knowledge of words and the conceptual relations between the ideas they represent and the ability to apply that knowledge. Indeed, Davis (1968) has reported that knowledge of word meanings and the ability to draw inferences accounted for much of the variance in his subjects' reading comprehension scores. To get some indication of the relative importance of language comprehension in reading and of the relative importance of language comprehension in reading and of the relation of this ability to the other skills tapped by our reaction-time tasks, we tested fast and average readers for comprehension of spoken discourse. In addition, we gave our subjects both the verbal and quantitative portions of the School and College Aptitude Test (SCAT). The verbal portion of this test contains a small number of word analogy problems, so performance does not depend heavily on reading speed in a direct sense. Likewise, performance in the quantitative portion of the test does not appear to depend very heavily on how quickly the problems can be read.

In our previous study on individual differences in reading ability, we chose the fastest readers we could find for comparison with a group of good but not outstanding readers. In the present study, we were interested in obtaining direct evidence regarding the factors responsible for differences in reading ability within a more normal range of variation. For this reason, we tested subjects from the population of freshmen and sophomores at our university. The groups of fast and average readers selected for further testing were subjects whose effective reading performance places them in the highest and lowest quartiles for this group. This sampling strategy has a disadvantage in that the separation in reading ability between groups is not as large as in the previous study. Since all subjects were undergraduates, both groups contained better readers than the average young adult in the population at large.

We have chosen a combined measure of speed and comprehension as our index of effective reading performance rather than reading speed or comprehension alone because we believe that the goal of a proficient reader is to understand the material as efficiently as possible in the shortest amount of time. A simple measure of reading speed fails to capture the ability of readers to understand what they have read. On the other hand, a raw comprehension score does not indicate the efficiency with which the reader was able to achieve understanding. An appropriate measure of reading ability should jointly depend on both speed and comprehension. Therefore, we have measured reading ability in terms of an effective reading speed score, defined as the speed of reading the test material multiplied by the score on a subsequent comprehension test.

Experiment 1

Method

Overview

All subjects were tested for effective reading speed on the long passage (see reading tests) and for verbal and quantitative aptitude (see aptitude tests), in that order, in an initial session of about 1 hr. All subjects returned for a second 2-hr. session consisting of the paragraph-reading test and the listening comprehension test; the order of these tasks was counterbalanced over subjects.

Subjects selected for the fast and average groups returned for three 1-hr. sessions approximately 1 wk. apart. In one session, subjects performed, in order, the letter-separation task with a blank line, the letter-separation task with a filled line, the letter-threshold task with a blank line, the letter-threshold task with a filled line, and the auditory letter-span task. The other two sessions consisted of the reaction time tasks; they were always given in the same order. In the first of these sessions, subjects were tested on the simple-pattern task, the letter task, and the synonym task in that order. The second session consisted of the homonym task and the multiple-letter display search task, also in order. Subjects were given short breaks between tasks and midway through the rather lengthy letter and multiple-letter tasks.

Reading tests. We used two different tests of effective reading speed: a long-passage test and a short-paragraph test. The long-passage test had been used in our previous research (Jackson & McClelland, 1975). The text consisted of an article of 4,286 words, "The Trojan Hearse," by Isaac Asimov (1975). The passage dealt with asteroids. This topic was chosen to be unfamiliar to as many potential subjects as possible. The comprehension test consisted of 10 short-answer questions and was completed immediately after reading the passage. The unfamiliar topic and our use of short-answer questions made the comprehension test more sensitive to changes in reading speed by reducing the likelihood that subjects could guess correct answers or know the correct answer from previously acquired knowledge about the topic. The long-passage effective speed score was the speed multiplied by the percentage correct on the comprehension test.

The short-paragraph test consisted of 11 paragraphs with an average length of 317 words. The paragraphs were modified selections from a number of scholastic aptitude test preparation books and covered a variety of topics. Each paragraph had a comprehension test of three short-answer questions. These questions were intended to gauge the reader's conceptual synthesis of the material as well as factual knowledge contained in it. Initially, 24 paragraphs and sets of questions were constructed. Based on the performance of a set of pilot subjects who were tested on all 24 paragraphs, 4 paragraphs were discarded and the remainder were divided into two sets of equal difficulty, each containing 10 paragraphs. Half of the subjects were tested using one of the paragraph sets, the other half were tested using the other set. The order of the paragraphs in each set was the same for all subjects. The first paragraph in each test was one of the 4 rejected paragraphs and was used for practice. The paragraph effective reading speed score was the mean effective speed (raw speed multiplied by the percentage correct comprehension) for the remaining 10 test paragraphs.

Instructions were the same for both reading tests. Subjects were told that the purpose of the reading test was to obtain an estimate of their actual reading speed. Subjects were instructed to read each passage as fast as possible, consistent with good comprehension, and were warned that afterwards they would be given a comprehension test. Subjects were instructed to write a brief answer to each comprehension question. No time limit was placed on the comprehension tests. Answers were scored from a key written by the experimenter. For the paragraph tests, each set of comprehension questions was completed immediately after reading the paragraph.

Subjects

Fifty-two subjects were tested. All subjects were freshman or sophomore students currently enrolled at University of California, San Diego, native speakers of English, right-handed, and had no courses in astronomy and no admitted background knowledge about asteroids (beyond the knowledge that asteroids are small bodies orbiting between Mars and Jupiter). All of the subjects who required corrective lenses were instructed to wear them in the experiments. Subjects were paid $2 per hr.

To select a group of fast readers and a group of average readers, based on their effective reading speeds from both reading tests, an average effective reading speed was computed for each subject by converting their effective reading speeds from each of the two reading tests into z scores and averaging them. Two groups of 12 readers who had the highest 12 and the lowest 12 average effective reading speeds were chosen from the first 48 subjects satisfying the requirements. The effective reading speeds for the slower group ranged from 33 words per minute (wpm) to 123 wpm on the long-passage test and from 83 wpm to 116 wpm for the paragraphs. The fast group speeds ranged from 180 wpm to 454 wpm on the long passage and from 146 wpm to 282 wpm on the paragraphs. Two of the subjects in the fast group were unable to return for further sessions, so 2 replacement subjects, whose performance placed them in the fast group, were substituted. Also, the 2 subjects with the lowest average effective reading speed scores were replaced because they performed so poorly on the comprehension tests, indicating either gross deficiencies outside the normal range of college students or gross inattention.

Our multiplicative effective reading speed score may not be the optimal formula for taking both reading speed and comprehension into account. In particular, the effective reading speed score may exaggerate the reading ability of subjects who read the test passage very quickly with minimum comprehension. Thus, it is possible that some of the subjects in the fast reader group actually have lower true effective reading speeds than some of the average readers but scored higher because they were willing to sacrifice some comprehension performance for greatly increased speed. Fortunately, however, the fast reader group tended to have higher raw comprehension scores (averages of 70.8% and 71.8% correct for fast readers on the long-passage and short-paragraph tests, respectively, compared to 45% and 59.1% for the average reader group with both differences significant, $t(22) = 4.18$ and $t(22) = 2.92$, $p < .01$), as well as higher raw reading speed scores (averages of 396.4 wpm and 290.4 wpm for the fast readers for each test, compared to 216.1 wpm and 169.3 wpm for the average group), $t(22) = 4.31$ and $t(22) = 6.32$, $p < .001$. Thus, the fast readers were both reading faster and understanding the material better.

Apparatus and Materials

For the threshold tasks and letter separation tasks, the stimuli were presented in a modified two-field Polymetric tachistoscope with Sylvania F4T5/D fluorescent lamps illuminating each channel. Modifications included a more durable timing circuit and an extension of the viewing distance to 71 cm. The reverse field of the tachistoscope was illuminated whenever the stimulus field was not, with preexposure and postexposure masking provided by an array of overlapping Xs and Os. The mask was three characters high and extended well beyond the widest separation used. The luminance of a blank white card was approximately 246 cd/m^2 in the stimulus field and 222 cd/m^2 in the masking field. The stimuli were typed on white 5 in. × 8 in. (12.7cm × 20.3 cm) cards with a 10-pitch IBM selectric typewriter using a Courier 72 element.

For each of the reaction-time tasks, stimuli were presented on a computer-driven display screen. The computer automatically recorded reaction times and responses from standard keyboards located in each of three soundproof booths. The stimuli were presented on Tektronix Model 602 Display scopes with P15 phosphor at a viewing distance of approximately 40 cm. Each stimulus letter subtended approximately .5° × 57°. Up to three subjects were tested simultaneously in a session in different booths. Auditory stimuli for the listening comprehension and letter-span tasks were recorded and played back binaurally via headphones on a SONY Model TC-650 tape recorder.

General Performance Tests

Aptitude tests. The verbal and quantitative aptitude tests were taken from the School and College Aptitude Test, Series II, Form 1C. The original test consisted of a verbal ability section of 50 word-analogy questions and a quantitative ability section of 50 questions. All questions were multiple choice. We divided the test into two alternate forms, each form having a verbal and quantitative section of 25 questions each. The time limit for each section was 10 min., half the suggested time limit for a whole section. Each subject was tested using one of the alternate forms, assigned randomly, following instructions supplied with the test. Subjects answered questions by marking standardized answer sheets supplied with the test.

To compare alternate forms, a separate group of sophomore subjects were recruited and tested on both forms in a single session lasting 1 hr. The forms were quite reliable ($r = .78$ for verbal, $r = .87$ for quantitative).

Listening comprehension. The listening comprehension test consisted of the same sets of paragraphs that were used for the paragraph-reading speed tests. Each set of 11 paragraphs was recorded on tape, in a normal speaking voice, at an average speed of 200 wpm. The comprehension questions were exactly the same as used for the reading test. Subjects were tested using the set of paragraphs that they did not read in the paragraph reading speed test. An equal number of subjects were tested with each set, assigned randomly.

Each subject was seated in a soundproof booth and listened to each paragraph over headphones. Five seconds after the end of each passage, the comprehension questions were displayed on a video monitor screen. Subjects wrote their answers to the questions on answer sheets provided by the experimenter. The questions remained visible until the subjects indicated that they were ready for the next passage. The questions were then erased, and the next passage played after a pause of 5 sec.

Sensory Tasks

General procedure. The subject sat looking into the tachistoscope and fixated on the center of the masking pattern. Instructions stressed that the tasks were difficult and would require full attention on each trial. When the subject felt ready for each trial, the subject pressed a foot switch and 300 msec later the stimulus was briefly exposed. For the letter-separation tasks, stimuli were presented for 200 msec.

Letter-separation tasks. For both the filled and blank-line versions of this task, stimuli consisted of 54 pairs of uppercase letters formed from combinations of two different letters from either the set A,B,C,E,F,G,H,M,N (blank line) or the set B,C,F,G,H,K,M,N,P (filled line). The letters were chosen to be confusing, making the discrimination more difficult. Eighteen pairs were used at each of three separations, with 3 additional pairs at each separation for practice. In the blank-line test, letters were separated by 17, 25, and 31 spaces (3.6°, 5.4°, 6.5°, respectively) with all other letter positions in the line blank. The midpoint between the letters coincided with the fixation point.

For the filled-line task, separations of 5, 9, and 13 spaces (1.2°, 2.0°, 2.8°, respectively) were used. Other letter positions were filled by the nonletter character "&", extending the field to 35 characters. Spaces were placed in the string of characters to approximate the visual pattern of a line of text and help the subjects locate the stimulus letters. For example, a typical stimulus card looked like the following:

&&& &&&&& &&B&& &&F&& &&&&& &&&.

During each task, the set of possible letters was displayed at the top of the masking field before and after each trial to ensure that all subjects were aware of the sample set. After each trial, subjects wrote down, on a form provided, which letter was presented on the right and which letter was on the left of the fixation point. Subjects were instructed to guess if they were not sure, selecting only letters from the sample set. In the blank-line task, the 9 practice trials were followed by the 54 test trials presented in random order. In the filled-line test, the pairs were blocked by spatial separation, so the subject would not have to search the display to find the letters. In each block, the 3 practice trials were followed by the 18 test pairs presented in random order.

Single-letter threshold tasks. For both versions of this task, the stimuli were single capital letters presented at the center of the stimulus field. For each test there were 36 stimuli, four of each of the letters in the same sets used in the corresponding letter-separation tests. For the filled-line threshold task, other positions in the stimulus line were filled with the nonletter character &, extending the line to 29 letter spaces, as in this example:

&&&&& &&&&& &&M&& &&&&& &&&&&.

As in the letter-separation tasks, the list of stimulus letters was displayed at the top of the masking field.

The same procedure was used for both threshold tasks. Subjects were instructed to fixate the center of the masking pattern and to respond verbally by saying the letter they saw, or saying that they did not see a letter. The threshold was approached using a modified binary search method, starting at 20 msec. The threshold was taken as the average of the last 20 trials.

Matching Tasks

General procedure. One to three subjects were tested at a time in separate booths. Each subject was seated in a soundproof booth, about 38 cm from the display scope. The response keyboard was placed in front of the subject who was able to move it to a comfortable position. The same two adjacent keys were used for responses. Subjects always used their right hand to respond and always responded *same* with the first finger and *different* with the second. Each stimulus trial was preceded by a fixation dot that served as a warning signal for the next trial. The fixation dot was displayed for 1 sec and then was immediately replaced with the stimulus pair. The stimuli were centered in the display around the fixation dot. The stimulus pair remained on the screen until all subjects responded. Subjects were instructed to respond as fast as possible without making an excessive number of errors. Each trial was followed by a 3-sec delay until the next trial. (Figure 1 summarizes the stimuli used in the matching tasks.)

Simple-pattern task. The stimulus pairs consisted of the four possible permutations of a plus sign and a square, and subjects responded *same* if the members of the pair were the same and *different* if they were different. The pairs were presented side by side, separated by one character space. There were 100 trials, 25 of each pattern configuration. The first 20 trials served as practice. The 80 test trials consisted of 40 same and 40 different pairs presented in random order.

Letter task. The stimulus items were pairs of letters using all permutations of uppercase and lowercase letters from the set A,B,D,E, and R. The letters were presented side by side, separated by one character space. Subjects responded *same* if the two letters were physically identical or if they were physically different but had the same name. Of the 320 test pairs, 80 were physically the same, 80 pairs had the same name, and 160 pairs were different. The test trials were presented in random order. The test trials were preceded by 20 practice trials containing the same proportion of each type of test pair.

Synonym task. Here, the stimuli were 160 pairs of words, and subjects were instructed to respond *same* if the words had the same meaning. The pair of words were presented one above the other, straddling the fixation point. To make the actual stimulus list, 160 synonym pairs were divided randomly into two groups of 80 pairs. One set of 80 pairs was kept together for same trials, whereas the other 80 pairs were scrambled for different trials. A list of 40 additional synonym pairs was used to yield 20 same and 20 different pairs for the practice trials. The test stimuli were presented in random order, following the practice trials.

Homonym task. Stimuli were pairs of words, and subjects were instructed to respond *same* if the words had the same pronunciation. The words were presented one above and one below the fixation point. For each pair of homonyms used (e.g., doe-dough) a pair of nonhomonyms was constructed to match the homonym pair as closely as possible in the number and placement of shared letters (e.g., toe–tough). This matching procedure ensures that responses based only on an analysis of similarity of the letter pattern, without regard to the sound of the letters, would be highly inaccurate. Subjects received 40 practice trials followed by 160 test trials, with an equal number of same and different trials. Pairs were presented in random order.

Other Tasks

Multiple-letter display task. On each trial, the subject viewed a target letter followed by a search set of two, four, or six letters. Subjects were instructed to respond "present" if the target letter was in the search set, or "absent" if the target letter was not present. The stimulus letters were randomly selected consonants. On each trial, the fixation point was followed by the target letter, displayed for 500 msec. The display was then blank for 1 sec, followed by the search set displayed for 200 msec. The search set was displayed in a circle, centered at the fixation point, with the six letter positions equidistant from the fixation point. For the smaller set sizes, the letters always occupied opposite positions in the six-position display. Each subject was tested with 36 practice trials followed by 288 test trials presented in random order. There were 96 trials of each set size, 48 trials with the target letter present in the search set, and 48 with the target letter absent. In the former type of trials, the target letter occurred equally often at each display position for each set size.

Auditory letter-span task. The letter-span task was similar to the standard digit-span task. On each trial, the subject listened to a prerecorded string of unrelated consonants and immediately after the last letter attempted to recall the string of letters in the order presented. Each letter string consisted of a set of consonants selected randomly without replacement, recorded at a fixed rate of one letter per sec. Each string was preceded by a warning tone and followed 1 sec after the last letter by a tone signaling the subject to recall the string. Each subject was tested with eight strings of six letters and eight strings of seven letters in length. The first three strings at each length served as practice. To reduce differences due solely to differential use of chunking strategies, the strings were prechunked into three or four letter substrings. For example, a six-letter string was presented one letter per sec, with a 1-sec pause after the first three letters.

Results

Performance on General Tests

The upper left quadrant of Table 1 presents the relationship between the five tests given to all of the subjects who were screened in the experiment, using the effective reading speed measure of performance on each reading test. Effective reading speed on the two reading tests were highly correlated ($r = .79$), with one test accounting for 62% of the variance (r^2) in the other. Both measures of effective reading speed were fairly highly

Table 1
Product-Moment Correlations for All 52 Subjects

	2	3	4	5	6	7	8	SPC
1. LPEF	.79	.67	.52	.40	.73	.74	.72	.52
2. SPEF		.59	.58	.40	.76	.45	.87	.70
3. LC			.47	.36	.36	.65	.47	.55
4. SCV				.38	.41	.47	.44	.55
5. SCM					.19	.43	.27	.43
6. LPSP						.12	.82	.28
7. LPC							.29	.55
8. SPSP								.29

Note. For $r \geq .32$, $p < .01$; for $r \geq .23$, $p < .05$. LPEF = long passage effective speed; SPEF = short paragraph effective speed; LC = Listening comprehension; SCV = SCAT Verbal score; SCM = SCAT Quantitative score; LPSP = long passage raw speed; LPC = long passage raw comprehension; SPSP = short paragraph raw speed; SPC = short paragraph raw comprehension.

correlated with comprehension performance in the listening test and with both verbal and quantitative aptitude performance. Although the relation with quantitative aptitude was somewhat weaker, even these correlations were significant.

The upper right quadrant of the table indicates the relation of these variables to raw speed and comprehension performance in the two reading tests. Each effective speed measure was highly correlated with both raw reading speed and comprehension for that test. Also, each effective reading speed measure was correlated to a lesser extent with raw speed and comprehension on the other reading test. In three of the four cases, the effective reading speed measure was more highly correlated with raw reading speed than with the reading comprehension score. Both raw reading speed and comprehension were correlated with listening comprehension, verbal aptitude, and quantitative aptitude, although the correlations were all higher for raw comprehension than for raw reading speed.

Finally, the lower right quadrant gives the relations between raw reading speed and comprehension on the two reading tests. For the long passage test, raw reading speed and comprehension were not significantly correlated; for the short paragraph test, the

Table 2
Stepwise Multiple Regressions on the Two Separate Measures of Effective Reading Speed for All 52 Subjects

Step	Variables in equation	R^2
	Long passage	
1	LC	.44
2	LC (.54), SCV (.27)	.50
	Short paragraph	
1	LC	.33
2	LC (.41), SCV (.38)	.47

Note. LC = listening comprehension; SCV = SCAT Verbal score. Numbers in parentheses are standardized beta weights for each variable after the second step.

correlation was significant but small. In the case of each reading test, raw reading speed correlated less well with raw comprehension than it correlated with comprehension in the listening comprehension test.

These correlations make several important points. First, it is clear that the effective reading speed scores pick up differences in speed and comprehension combined. This is evidenced by the high correlations of effective reading speed with raw speed and with raw comprehension, coupled with the rather low correlations of speed and comprehension on each test. Second, the fact that reading speed is correlated with performance on the listening comprehension test indicates that when their speed of input is controlled, subjects who read quickly tend to be slightly better comprehenders than slower readers. However, when the subjects set their own pace, there is not much of a relationship between the comprehension criterion and reading speed, as indicated by the low correlation of reading speed and comprehension within each reading test.

To determine how listening comprehension, verbal aptitude, and quantitative aptitude relate to effective reading speed, the data were analyzed using stepwise regression analysis. Here, and elsewhere in this article, the regression analyses were performed in a stepwise fashion as follows: Variables were entered into a regression solution, the dependent variable entered one at a time and the variable having the largest partial correlation with the residual variance in the dependent measure entered on each step. This procedure continued until no variable had a significant partial correlation with the residual.

The analyses of the two measures of effective reading speed are presented in Table 2. In both analyses, the listening comprehension score was entered first, but a sizable component of the remaining residual variance was correlated with performance on the SCAT Verbal test. Together, these two variables account for about 50% of the variance in both effective reading scores. These two factors actually accounted for a much larger proportion of the variance in common between the two measures of effective reading speed than these r^2 figures would indicate, since one reading test only accounts for 62% of the variance in the other.

These preliminary analyses of the entire sample of subjects reveal that a large proportion of the variance in effective reading speed is due to a general language comprehension ability that can be tapped in a listening comprehension test and to verbal reasoning ability. However, these abilities may depend, in turn, on more basic processes measured by our other tasks. In addition, there remains at least another 25% of the variance in effective reading speed that may be more specific to reading. This variance, too, may be due to more basic processes measured by our tasks but not directly related to comprehension skills or verbal reasoning ability.

Sensory Tasks

The results of the sensory tasks replicated our previous findings in showing no reliable differences between fast and average readers. Furthermore, the results do not indicate that fast and average readers are differentially sensitive to the effects of lateral masking. In the single-letter threshold tasks, thresholds for the fast reader group and average reader group were not significantly different. With the blank surrounding line, the mean fast reader threshold was 67.9 msec ($SD = 4.4$) versus 66.0 msec ($SD =$

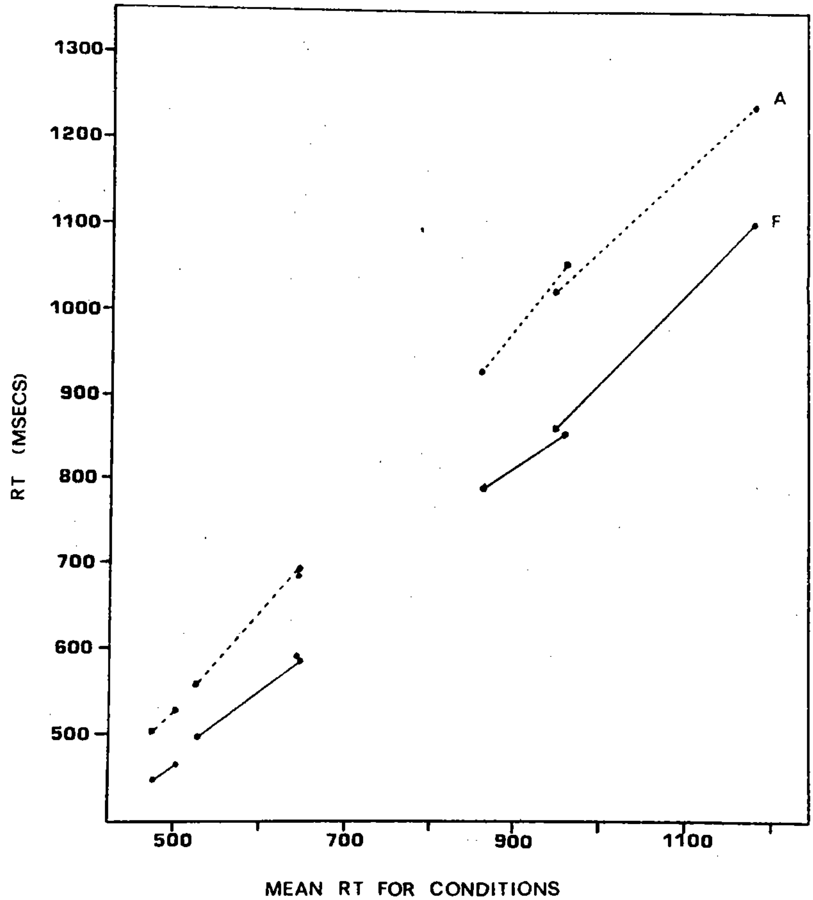

Figure 2. Mean reaction times for the fast (F) and average (A) groups for each matching task condition as a function of combined mean reaction time.

4.1) for the average group, $t(22) < 1$. Thresholds were longer when the letter was imbedded in the filled line, 83.2 ($SD = 5.2$) for the fast group and 84.7 ($SD = 4.1$) for the average group. The difference was not significant, $t(22) < 1$.

In the letter-separation tasks, fast and average reader groups did not differ significantly in the number of correct responses made at any of the separations. In the blank-line task, only the main effect of separation was significant, $F(2, 44) = 53.8$, $p < .001$. There was no difference between groups, $F(1, 22) = .59$, or interaction of reading group with separation, $F(2, 44) = 2.3$. The same pattern of results occurred for the filled-line task: a main effect of separation, $F(2, 44) = 9.6$, $p < .001$; no difference between groups, $F(1, 22) = 1.1$; and no interaction, $F(2, 44) = .49$. There was a slight advantage for fast readers at the widest separation (2.8°) in the filled-line task. This difference appeared to be due to a greater tendency for fast readers to cheat and report only the letter presented on the right side, thereby guaranteeing one correct letter. When the data were rescored, counting as correct only trials when subjects reported both letters correctly, there was no significant difference between fast and slow readers at this separation.

Matching Tasks

Reaction-time and error data from the matching tasks are shown in Table 3. Results are broken down by task and further by condition within task (same vs. different

Table 3
Mean Reaction Times and Error Rates for Experiment 1

Task	Reaction times		Error rates	
	Fast	Average	Fast	Average
Simple pattern				
Same	450	506	5.0	3.3
Different	469	532	7.1	3.3
Letter				
Physical same	492	558	2.4	1.6
Name same	581	698	13.9	10.6
Different	592	690	5.1	3.9
Synonym				
Same	788	927	8.2	10.5
Different	855	1055	4.1	3.6
Homonym				
Same	861	1019	5.8	9.7
Different	1106	1245	16.0	20.6

with a further subdivision of the same condition for the letter-match task into physical same and name same, giving a total of nine different conditions). Inspection of these results reveals that fast readers had an advantage over slow readers in every case and that the difference increased in size with the average amount of time required to reach a decision. To represent this graphically, we have arranged the conditions along the x-axis on a linear scale of increasing mean reaction time for the condition (Figure 2). There is clearly a divergent trend in these results. To confirm this fact statistically, we subjected the mean reaction times for each subject to an analysis of variance. The main effect of groups was significant, $F(1, 22) = 9.06$, $p < .01$, reflecting the overall fast reader advantage. Likewise, the main effect of conditions was significant, $F(8, 176) = 171.0$, $p < .001$. The Groups × Conditions interaction was partitioned into two components—(a) a linear component reflecting the increase in the fast reader advantage with increasing mean processing time and (b) a residual component reflecting the remainder of the variance over tasks in the size of the fast reader advantage. The linear component was significant, $F(1, 176) = 10.79$, $p < .01$, but the residual component was not, $F(7, 176) < 1$.

Consideration of the error rate data (Table 3) suggests that the divergence would have been even greater had the subjects in the two groups maintained equivalent error rates in all tasks. In particular, the fast readers showed more errors than the average readers on the simple-pattern matching task, $t(22) = 1.90$, $p < .05$, one-tailed, in which mean reaction times were fastest and showed considerably fewer errors on the homonym task, $t(22) = -1.68$, $p < .07$, one-tailed, in which mean reaction times were slowest. The error rates for the letter task and synonym task conditions were not significantly different. Thus, the error data reinforce the conclusion that there is a diverging trend in the reaction times. We consider the error data further in the section labeled *controlling for accuracy.*

Other Tasks

Multiple-element display task. The results of the multiple-element display task were consistent with the view that subjects compared the elements of the display to the target letter in serial fashion, terminating the comparison process as soon as a match was found. (See Sternberg, 1969, for a discussion of the logic of this analysis.) Subjects were generally faster responding when a target was present than when it was absent, $F(1, 22) = 28.7$, $p < .001$ (see Figure 3). In addition, there was a strong linear increase in reaction time with number of display elements, $F(1, 44) = 168.7$, $p < .001$, with no reliable nonlinear component, $F(1, 44) = 2.71$, $p > .10$. The difference between positive and negative responses increased linearly with set size as is predicted by the self-terminating comparison model, $F(1, 44) = 24.3$, $p < .001$, and there was no reliable nonlinear relation between set size and response type, $F(1, 44) = 1.76$, $p > .10$.

Comparison of the fast and average reader groups does not reveal the diverging trend apparent in the matching tasks. Reaction times for fast readers were generally faster than those for slow readers, $F(1, 22) =$

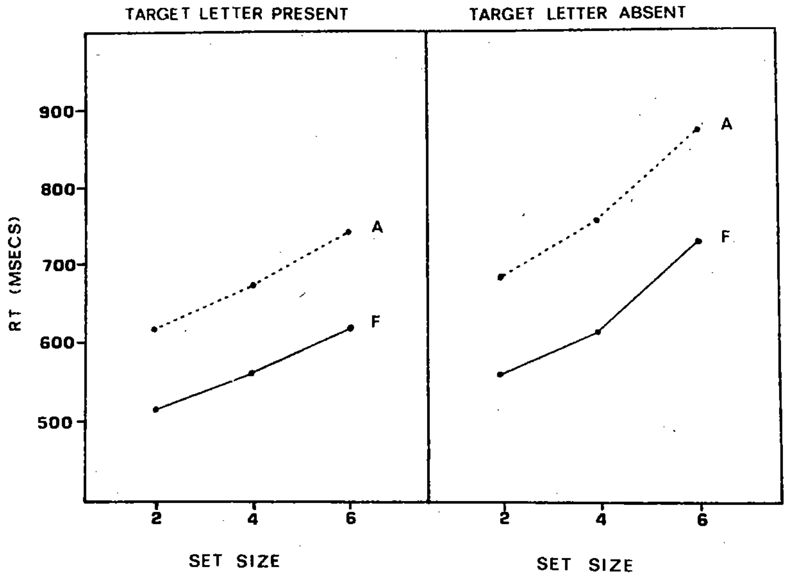

Figure 3. Mean reaction times for the fast (F) and average (A) groups in the multiple display task, as a function of the presence or absence of the target letter and set size.

5.53, $p < .05$, but there were no reliable interactions of the group factor with set size, response type, or both ($F < 1$) in each case. Thus, it appears that the rate of the comparison of the target and display characters does not vary with individual differences in reading ability. However, some component of processing that is independent of display size does vary between fast and average readers.

Auditory short-term memory. Fast readers had a small advantage over average readers in the number of letters accurately reported in the auditory letter-span task. The percentage of correctly reported letters averaged over lists of Lengths 6 and 7 was 87.3 for the fast group and 78.8 for the average group, $t(22) = 1.87$, $p < .05$, one-tailed. On the average, fast readers correctly reported 5.70 letters of the six-letter strings and 5.64 letters of the seven-letter strings, whereas the average group reported 5.20 and 5.04 letters, respectively, $t(22) = 1.66$, $t(22) = 1.57$; $.05 < p < .10$, one-tailed.

Correlation and Regression Analyses

Controlling for accuracy. To what extent might the reaction-time results we have obtained be accounted for by a tendency of faster readers to set a lower accuracy criterion than slower readers? To help address this question, we have used correlational techniques to partial out the variance in reaction time that can be attributed to individual differences in accuracy.

Before we consider these analyses, several cautions must be noted. First, there are several possible reasons why subjects might make errors. Errors due to a low accuracy criterion can appear in any reaction-time task. In addition, errors may result either from insufficient stimulus information (as might arise from a brief or degraded presentation) or from insufficient knowledge on the part of the subject. It is doubtful that insufficient stimulus information was a problem in any of our tasks; indeed, in all but one case, the stimuli remained visible until a response was made, and they were not degraded in any way that would make accurate identification difficult. It is also unlikely that the subjects lacked the knowledge required to perform accurately in the simple match, letter match, and multiple display tasks. For these tasks, then, only differences in accuracy criterion can plausibly account for individual differences in ac-

Table 4
Simple Correlations of Reaction-Time Performance, Accuracy, and Reaction Time Controlling for Accuracy with Both Measures of Effective Reading Speed

Task	r of accuracy with RT performance	r of accuracy with		r of RT performance with		Partial r of RT performance with	
		LPEF	SPEF	LPEF	SPEF	LPEF	SPEF
SIM	−.50	−.50	−.38	.38	.37	.16	.20
MLD	−.40	−.23	−.21	.30	.37	.22	.32
PHY	.13	−.04	−.11	.34	.32	.35	.34
NAM	.20	.01	−.05	.47	.49	.47	.49
SYN	−.38	.07	.17	.41	.49	.47	.59
HOM	−.07	.49	.52	.19	.23	.26	.32

Note. A positive-valued correlation coefficient indicates a positive relationship between superior performance on one measure (e.g., faster reaction time, greater accuracy, higher effective reading speed) and superior performance on the other. Thus, higher effective reading speed tends to be associated with faster reaction times (RTs). LPEF = long passage effective reading speed; SPEF = short paragraph effective reading speed; SIM = simple pattern RT; MLD = multiple letter display RT; PHY = physical-same letter match RT; NAM = name letter match RT; SYN = synonym match RT; HOM = homonym match RT. For $r \geq .34$, $p < .05$. $N = 24$.

curacy. For the homonym and synonym tasks, matters are somewhat more complex. Here there were, as we shall see, some individual differences in accuracy apparently due to individual differences in knowledge about words. We return later to this matter in considering these tasks individually.

Even for tasks in which accuracy differences can only be attributed to differences in criterion, correlational attempts to factor out these sources of individual differences face certain difficulties. If reaction time and accuracy are negatively correlated, and accuracy is negatively correlated with reading speed, the strength of the relationship between speed of task performance and reading speed will be reduced by taking the partial correlation of task speed with effective reading speed, controlling for accuracy. This procedure can potentially underestimate true differences in reaction time. If fast readers are both faster at the task for a given accuracy criterion and more prone to set their accuracy criterion low, the partial correlation of task speed and reading speed controlling for task accuracy may underestimate the true relationship between task speed and effective reading speed.

There remains the problem of scaling the reaction-time and accuracy measures so that their relationship will be approximately linear over the accuracy levels operating in our tasks. Pachella (1974) has reviewed studies that indicate that reaction time and accuracy as measured by d' are approximately linearly related in tasks like our simple match and letter match tasks. For this reason, we have used d' as our measure of accuracy and reaction time as the measure of speed. Note that in the correlational analyses, we show correlations of shorter responses with faster reading as positive so that a positive correlation always signifies that superior performance on one measure is related to superior performance on another.

With these considerations in mind, we turn to the results of our analyses, presented in Table 4. The table presents the raw correlations of reaction-time performance on each task with accuracy on that task and with each measure of effective reading speed, as well as the correlation of accuracy with effective reading speed. The partial correlation of reaction-time performance with effective reading speed controlling for accuracy is also reported. For each task, results are averaged over decision type (same and different). For the letter-match task, the physical-same and name-same reaction times were not averaged, since these measures presumably reflect somewhat different processes. The name-match variable is the average of reaction times for stimuli that were either same in name but physically different or different both physically and in name, since both kinds of stimuli require use of name information for correct responding. The physical-match reaction-time score is derived only from same reaction times on trials when the stimuli were physically identical. For the multiple-display task, the score is the reaction time averaged over both response types and all three display sizes. Different patterns of results and different considerations apply to each task, so we consider each in turn.

In the simple match task, there was a strong negative correlation between reaction time and accuracy for both measures of effective reading speed. In addition, there was a significant correlation between reading speed and accuracy, indicating that faster readers had lower accuracy criteria than slow readers. Controlling for this difference in accuracy, the partial correlation of reaction time on this task with each of the measures of effective reading speed is considerably reduced. These small partial correlations are consistent with the conclusion that the relationship between reaction time in this task and reading speed is primarily the result of a speed–accuracy trade-off. However, as indicated earlier, these partial correlations may slightly underestimate the relationship between speed in this task and reading speed.

The pattern of results on the multiple-display task were very similar to those obtained in the simple match task. Again, there was a negative correlation of accuracy with reaction-time performance, and, again, there was some indication that faster readers tended to have lower accuracy criteria than slower readers, since the correlation of accuracy with both reading speed measures was slightly although nonsignificantly negative. As in the simple-match task, the correlation of reaction-time performance with effective reading speed was somewhat reduced when accuracy was partialed out; the partials were rather small and neither was significant at the .05 level. Again, however, it is possible that these partials overcorrect for accuracy differences.

The results of the letter-matching task are considerably more clear-cut. On this task, there were no reliable correlations between task speed and accuracy or between accuracy and effective reading speed, either for responses requiring physical information or responses requiring identity information. For these two tasks, controlling for accuracy had little effect on the correlation between effective reading speed and either reaction-time score; in both cases, the partials were significant. Thus, there is no evidence that the positive relationship between performance in the letter-match task and effective reading speed can be accounted for by individual differences in accuracy criterion.

The synonym task presents a somewhat more complicated picture. There was a negative correlation between accuracy and reaction-time performance. However, accuracy in this task was unrelated to reading speed, so that there is no indication that faster readers respond more quickly simply because they have lower accuracy criteria than slow readers. Indeed, the partial correlation of reaction-time performance with effective reading speed actually increases slightly when accuracy is partialed out. However, the correlation of accuracy on the synonym task and effective reading speed may underestimate any individual differences in accuracy criteria between fast and slow readers; fast readers may respond inaccurately because they have low accuracy criteria, whereas slow readers may respond inaccurately because they do not know the meanings of the words. Indeed, there is some indication that individual differences in accuracy on this task are partially related to individual differences in knowledge of the meanings of words; the correlation of accuracy in the synonym task and accuracy in the SCAT Verbal test, which relies on knowledge of word meanings, was .36 ($p <$ .05). To assess potential differences in accuracy due to criteria independent of accuracy differences owing to word knowledge, we partialed out individual differences in knowledge of word meanings, as measured by the SCAT Verbal test, from the accuracy scores on the synonym task. We then recomputed the correlation between effective reading speed and the residual accuracy scores. Even these new partials showed little indication that faster readers had lower accuracy criteria than slower readers in the synonym task: The correlation of the residual accuracy score with effective reading speed was $-.14$ for the long passage test and $-.09$ for the short paragraph test. Controlling for this residual accuracy score, the correlation between reaction-time performance and effective reading speed remains significant for both measures of effective reading speed ($r = .40$ for the long passage test, $r = .51$ for the short paragraph test).

In considering the results of the homonym task, many of the same considerations arise. Here, however, it appears that differences in knowledge (in this case for the sounds rather than the meanings of words) play an even more important role than they do in the synonym task. First, the correlation of accuracy with effective reading speed was strongly positive. In addition, the correlation of accuracy with performance in the SCAT Verbal test was positive ($r = .42$, $p < .05$), even though the SCAT Verbal measures knowledge of word meanings, whereas the homonym reaction-time task is more sensitive to knowledge of the sounds of words. Thus, it appears that subjects who know more about word meanings tend to know more about their sounds as well and therefore tend to be more accurate in the homonym matching task.

The correlation of effective reading speed and accuracy on the homonym task makes the reaction-time results suspect. First, individual differences in accuracy criterion may be hidden by individual differences in knowledge of the sounds of words. Since we had no test that actually measured knowledge of word sounds, we have no way to control for this confounding variable. Another problem is that fast and slow readers may be yielding correct reaction-time data on a different sample of stimulus materials. If slow readers tend to make more errors on stimuli that are hardest for fast readers to judge correctly, the fast readers would tend to have relatively long reaction times averaged into their mean reaction time when slow readers would simply have missing observations. Thus, it is possible for the experiment to underestimate the difference in reaction time between good and poor readers because of an accuracy-related sampling bias against good readers. To remedy this problem, we seem to need another experiment.

In summary, then, the results reported in this section indicate that the fast reader advantage in the physical-match, name-match, and synonym tasks cannot be attributed to lower accuracy criteria on the part of the fast readers. With regard to the other tasks, these analyses suggest that our findings are somewhat less clear. Correcting for accuracy in the simple-match and multiple-display tasks reduces the correlation of reaction time and reading speed to nonsignificant levels, but these partials may overcorrect for true reaction-time differences. Accuracy differences in the homonym task make any conclusion that we might draw from the reaction-time results of that task suspect. However, the accuracy differences observed in this task are interesting in their own right, since they suggest that faster readers have greater knowledge of the sounds of words than slower readers do.

Regression analyses of effective reading speed. We have now considered a large number of task variables that are more or less strongly related to individual differences in effective reading speed. The question arises whether all of these variables simply measure, to varying degrees, the same underlying ability that is related to individual differences in effective reading speed or whether some reflect sources of variation in effective reading speed independent of those picked up by the others. To address this question, we have used Pearson product-moment correlations, just as we did in computing the coefficients in Table 4. These correlation coefficients (Table 5) are somewhat inflated estimates of the true population coefficients, since the middle

Table 5
Pearson Product-Moment Correlations

Item	2	3	4	5	6	7	8	9	10	11	12	13	14	15	STM
1. LPEF	.88	.75	.56	.43	−.02	−.22	.38	.34	.45	.41	.19	.49	.30	.18	.33
2. SPEF		.70	.68	.47	−.06	−.28	.37	.32	.49	.49	.23	.52	.37	.20	.45
3. LC			.47	.34	.00	−.08	.18	.16	.17	.26	.17	.31	.00	−.03	.16
4. SCV				.45	.07	−.10	.22	.19	.35	.23	.26	.42	.25	.20	.24
5. SCM					−.03	−.08	.26	.24	.37	.34	.51	.23	.51	.50	.17
6. PSP						.37	−.14	.02	−.15	−.01	.05	−.14	.15	.01	−.12
7. SLT							−.03	.20	.19	.07	.25	−.41	.29	.29	−.23
8. SIM								.90	.78	.74	.56	−.11	.51	.01	.27
9. PHY									.91	.74	.59	−.19	.57	.17	.28
10. NAM										.77	.64	.02	.74	.40	.42
11. SYN											.68	−.08	.64	.30	.35
12. HOM												−.07	.49	.21	.37
13. AHOM													−.09	.00	.32
14. MLD														.73	.11
15. Slp															.05

Note. A positive-valued correlation coefficient indicates a positive relation between superior performance on one task (higher score, lower threshold, or shorter reaction time) and superior performance on the other. LPEF = long passage effective reading speed; SPEF = short paragraph effective reading speed; LC = listening comprehension; SCV = Verbal Aptitude score; SCM = Quantitative Aptiude score; PSP = peripheral letter span; SLT = single letter threshold; SIM = simple pattern RT; PHY = physical-same letter match RT; NAM = name letter match RT; SYN = synonym match RT; HOM = homonym match RT; AHOM = accuracy on the homonym task; MLD = multiple letter display RT; Slp = multiple display "slope"; STM = auditory letter span. For $r \geq .34$, $p < .05$. $N = 24$.

range of scores on the effective reading speed variables have been excluded. Comparison with Table 1 indicates that the correlations of the effective reading speed scores with verbal and quantitative reasoning ability and with listening comprehension, as well as the correlation of the two effective reading speed scores with each other, are increased when the middle range of scores are excluded. This magnification makes the coefficients in Table 5 useful for comparing the relative contribution of each variable to reading speed. An alternative analysis using point-biserial correlation coefficients would fail to make use of the information concerning the differences within the fast and average reader groups, which are quite substantial.

As in Table 4, for each reaction-time task the scores are collapsed over same and different responses. For the non-reaction-time variables, several variables have been combined as well. The peripheral span and single-letter threshold variables are composite scores formed by averaging the z scores for the blank-line and filled-line conditions over all separations. One other reaction-time variable, called the multiple-display slope, is the difference between reaction time for the six- and two-element displays in the multiple-display task, averaged over response type. This slope variable may be taken as an indication of the rate of comparison of the target and display elements within the framework of the standard Sternberg (1969) analysis of these tasks. Finally, the last variable included in the correlation table is the accuracy on the homonym task. This accuracy variable was singled out for inclusion because it has a significant correlation with each of the effective reading speed scores and because it is independent of reaction time in this task so that it picks up sources of individual differences that the homonym reaction-time variable does not pick up.

Examination of Table 5 reveals a number of interesting facts. First, nearly every predictor variable has a significant ($p < .05$, one-tailed) correlation with one or both effective reading speed scores, with the exception of the sensory variables, the homo-

Table 6
Results of a Stepwise Regression on Two Measures of Effective Reading Speed for the 24 Test Subjects

Coefficient of	Step entered	Long passage test	Short paragraph test
LC	1	.60	.53
NAM	2	.35	.39
AHOM	3	.29	.35
R		.87	.86

Note. Standardized beta weights after the third step of the analysis. LC = listening comprehension; NAM = name = letter match reaction time; AHOM = accuracy on the homonym task.

nym reaction-time variable, and the multiple-display slope variable. The best predicting task variables appear to be those involving letter-name or word-meaning access (name-match reaction time and synonym reaction time), although it is clear that both listening comprehension and the verbal reasoning tests are better single predictors of reading ability than any of the specific processing tasks. Correlations with raw reading speed and comprehension performance are not presented because subjects were selected on the basis of combined performance on reading speed and comprehension. This selection procedure has the effect of forcing a larger positive correlation between speed and comprehension than would exist if subjects had been selected only on the basis of one of these variables and of partially confounding correlations of independent variables with each of the two terms in effective reading speed. Nevertheless, informal inspection of the correlation coefficients revealed two interesting facts: The raw speed scores correlated much more highly with the reaction-time measures than did the raw comprehension scores and the raw comprehension scores correlated more highly with the listening comprehension and verbal abilities scores than did the raw reading speed scores.

Some of the relationships among the predictor variables are also worth noting. First, only the SCAT Verbal score shows a significant correlation with listening comprehension. The SCAT Verbal score correlated reasonably well with the reaction-time variables from tasks requiring letter name-code access (replicating Hunt et al. 1975, with a different verbal aptitude test). Surprisingly, the Verbal score did not show a significant correlation with the raw reaction-time score for the synonym task, although a firm knowledge of word meanings seems to be a strong requirement for performance on the verbal abilities test. However, this correlation seems to have been attenuated by the speed–accuracy trade-off present in the synonym reaction-time task. If residual reaction-time scores for the synonym task are used, with accuracy partialed out, the verbal score has a higher correlation with performance in the synonym task ($r = .40$, $p < .05$). Also this residual synonym-task variable has a high correlation with listening comprehension performance ($r = .37$, $p < .05$). Finally, the short-term memory score shows a moderate relationship to the reaction-time scores involving letter name-code access and a stronger relationship than most non-reaction-time variables to the homonym reaction-time score, perhaps pointing to the role of verbal encoding in short-term memory (Conrad, 1972). On the other hand, the short-term memory score has a low correlation with listening comprehension, perhaps suggesting that rote memory for unrelated linguistic elements plays little part in the ability to comprehend (Perfetti & Goldman, 1976).

Stepwise multiple-regression analyses were performed to find those variables that together best accounted for effective reading speed. Analyses were performed separately for each of the two effective reading speed measures. In these analyses (see Table 6), the variable with the largest correlation with the remaining variance in effective reading speed was entered into the regression equation at each step. The results indicate that the listening comprehension score, the name-match reaction-time variable, and the homonym accuracy variable were the first three variables entered into the regression equations. These results were not affected by the previously mentioned presence of speed–accuracy trade-offs in the simple-match, synonym-match, and multiple-display tasks; an alternative regression analysis, using residual reaction-time scores for each subject with accuracy partialed out, produced the same regression results.

These analyses once again indicate that listening comprehension is the single most powerful predictor of effective reading speed in our battery of tasks. The analyses also indicate that a measure of letter-name access provides a relatively independent contribution to the prediction of effective reading speed, accounting for a significant portion of the variance not picked up by the listening comprehension measure. The last variable entered into the equation was the accuracy in the homonym task. It is difficult to be sure what this variable reflects. Since all stimuli used in this experiment were words and since many of them were rather exceptional in spelling-to-sound correspondence (e.g., one, tough, doe, dough), it is likely that this variable reflects differences in knowledge of the pronunciations of particular words.

The listening comprehension, letter-name reaction-time, and homonym accuracy variables account for 77% of the variance (r^2) in one effective speed measure and 74% of the variance in the other measure. Although these percentages are undoubtedly inflated over their population values due to the elimination of the middle range of scores, it is worth noting that for this sample of subjects, the correlation of the two effective speed scores with each other was only .88, indicating that one measure of effective speed only accounted for 77% of the variance in the other measure. Thus, the regression solutions appear to account for nearly all of the variance in effective reading speed scores that is shared jointly by the tests. The remaining variance that is not accounted for may be due to systematic differences between the tests or to true error of measurement.

After these three variables were entered into the regression equation, none of the other variables accounted for a significant amount of the residual variance in effective reading speed. In particular, the name-match variable accounted for the portion of the variance in effective reading speed previously assigned to the verbal aptitude score (see Table 2). Both verbal aptitude and name-match reaction time showed high partial correlations with reading speed after listening comprehension was entered in Step 1. However, when the name-match reactiton-time variable was entered in Step 2, the significant partial correlation of verbal aptitude with the remaining variance in effective reading speed disappeared.

As shown in Table 5, simple-match, physical-match, and synonym-match reaction-time variables have reliable correlations with both effective reading speed measures, indicating that each of these variables is measuring some processing skill that is correlated with individual differences in reading ability. However, in the regression analysis, none of these variables had a significant correlation with the variance in effective reading speed remaining after the name-match variable was entered in Step 2. It appears, then, that the name-match variable is tapping the same component of effective reading speed as the other three tasks, at least after those components related to listening comprehension are partialed out. The name-match reaction time may be the best measure of this component or it may happen, by chance, to have the largest correlation of the four reaction-time variables with the remaining variance in effective reading speed after listening comprehension is entered into the regression equation. To determine whether the name-match variable is actually measuring significantly more of whatever these variables measure that is related to reading, we computed the partial correlation of the name-match variable with each measure of effective reading speed controlling for listening comprehension and either the simple-match, physical-match or synonym-match variables (see Table 7). In all of the three cases, the name-match variable still accounts for a significant amount of the remaining variance in effective reading speed. In interpreting the results of this partial correlation analysis, it should be

Table 7
Partial Correlations of Name-Match Reaction Time and Both Measures of Effective Reading Speed Controlling for Other Reaction-Time Variables

Controlling for	Long passage test				Short paragraph test			
	SIM	PHY	SYN	HOM	SIM	PHY	SYN	HOM
LC and RT score	−.36*	−.48**	−.41*	−.57**	−.43*	−.62***	−.32	−.54**

Note. LC = listening comprehension; RT = reaction time; SIM = simple pattern RT; PHY = physical-same letter match RT; SYN = synonym match RT; HOM = homonym match RT.
* $p < .05$. ** $p < .01$. *** $p < .001$.

noted that the reliabilities of the reaction-time measures, as estimated by odd–even reliability coefficients, were high ($r = .86$ for the simple-match variable; $r = .92$ for the physical letter-match variable; $r = .94$ for the name letter-match variable; $r = .98$ for the synonym-match variable; $r = .95$ for the homonym-match variable; and $r = .89$ for the multiple-display variable).

Although this partial correlation analysis suggests that the letter name-match variable is the best measure of whatever component of reading ability is being picked up by the reaction-time tasks, we may not want to place too much weight on the apparent relative importance of the letter name-match task. The major reason for proceeding with caution when interpreting these results is purely statistical; since these partial correlations involve highly correlated independent variables, the partial correlations may be somewhat unstable and standard significance tests may not indicate this instability. Therefore, we interpret these results as merely suggesting that for our sample of subjects, the name-match variable seems to be the best measure of a component of reading ability that is picked up to a lesser extent by some of the other reaction-time tasks as well.

Discussion

Performance on the tasks that we included to measure visual sensory processes showed no relation to reading ability. The results replicate our previous finding that faster readers have neither lower thresholds for identifying single letters nor superior peripheral sensitivity. Further, there is no indication that faster readers are less affected by lateral masking in foveal and peripheral vision. Thus, we have failed to find any reason to reject Woodworth's (1938) conclusion that "the limiting factors in speed of reading are not to be sought . . . in the peripheral processes of retinal stimulation" (p. 715).

With the exception of these sensory tasks, however, we found reliable differences in performance between fast and average readers in almost all of our tasks. In our matching tasks, we found that faster readers were faster on all the tasks and that the difference between fast and average readers increased as the overall mean reaction time increased. However, after controlling for accuracy criterion, the relationship between effective reading speed and performance in the simple-matching task was small and nonsignificant. Physical-match performance was correlated with reading ability, although to a lesser extent than name-match performance. In addition, the correlation between effective reading speed and synonym-matching performance could not be attributed to differences in accuracy criteria. Over the four tasks, then, both the size of the reaction-time difference between fast and average readers and the strength of the correlation between performance and effective reading speed increased with mean reaction time. The one exception to this pattern was provided by the homonym task. This task produced the largest overall reaction times, and the group means showed the largest difference between fast and average readers, but there was high variability among the members of each group. As a result, the correlation of performance on this task with effective reading speed was only marginally reliable. However, accuracy in the homonym matching task had a strong positive relationship to effective reading speed, clouding interpretation of the reaction-time results obtained in this task.

The multiple-letter display task produced large increases in mean reaction time as a function of increasing display size. However, this task produced no evidence of divergence of the two groups as a function of increasing mean reaction time. Faster readers responded more quickly than slower readers by about the same amount (100 msec) in all conditions, and there were no significant interactions between effective reading speed and display size or response type. Consideration of the error data calls into question the meaningfulness of the overall fast reader advantage in this task. Faster readers tended to make more errors than slower readers, and when error rate is partialed out, the correlation of mean reaction-time performance on this task with effective reading speed becomes nonsignificant. However, the trend in errors was not itself statistically reliable, and the possibility remains that the partial correlation procedure allows a small relation between speed and accuracy in this task to mask true performance differences beween groups.

The correlation and regression analyses indicate that the listening comprehension score is highly correlated with effective reading speed. The listening comprehension score itself is highly correlated with the SCAT Verbal score and somewhat correlated with reaction time on the synonym-matching task but does not appear to be related to reaction-time performance on any of the other tasks. Controlling for performance on listening comprehension, the name-match reaction-time variable accounts for a significant portion of the variance in effective reading speed. This reaction-time component is also picked up to a lesser extent by the synonym-match, physical-match, and simple-pattern reaction-time variables. Controlling for listening comprehension performance and name-match performance, accuracy on the homonym task retains a significant relationship with effective reading speed. Together, the listening comprehension score, name-match reaction time, and accuracy on the homonym task account for nearly all of the nonerror variance in effective reading speed shared by our two reading tests.

Listening Comprehension

The strong relationship between performance on the listening comprehension test and effective reading speed is evidence that the most important determinants of individual differences in effective reading speed for our sample of subjects lie in some general, modality-independent, language comprehension skills. Specification of the exact nature of these general comprehension skills is beyond the scope of the present article. We can say, however, that this skill appears to depend to some extent on knowledge and/or use of word meanings; the listening comprehension score was correlated with both the SCAT Verbal score and marginally related to the synonym reaction-time variable. However, the listening comprehension score is accounting for more of the variance in reading ability than can be explained by its correlations with performance in tasks requiring knowledge of word meanings. One other skill that might contribute to the correlation of listening comprehension and effective reading speed is the ability to maintain continuous attention to the task of understanding. In any case, whatever the listening comprehension task is measuring appears to be almost completely unrelated to the processing skills that contribute to the correlation of effective reading speed and performance on our visual information processing tasks (other than synonym matching) or to auditory short-term memory (Perfetti & Goldman, 1976).

Letter Matching

Most of our matching tasks appear to be sensitive to a processing ability that is correlated with individual differences in reading ability but that is uncorrelated with performance on the listening comprehension task. This ability is apparently tapped most strongly by the name-match variable and to a lesser extent by the physical-match, simple-pattern, and homonym-match variables. The synonym-match variable presents a more complex picture and is discussed more fully later.

How can we characterize the ability that the name-match task appears to tap? Since this task involves visual information processing, we might be tempted to point to some possible visual-sensory determinant of performance. However, performance in this matching task did not correlate with performance in any of our tasks designed to tap sensory processes. A more plausible possibility would be some general "speed of processing visual information" beyond the mere sensory level. This interpretation is consistent with the diverging trend over tasks in the reaction-time differences between fast and slow readers; as the amount of processing required by the task increases, as indexed by mean reaction time, the reaction-time advantage for faster readers increases. However, there are two aspects of our results that are not consistent with this interpretation. First, we found no difference between fast and average readers in the amount of increase in reaction time with display size in the multiple-display task, so it is clear that the diverging trend is not a result of simply more processing per se. Second, a "speed of visual processing" component would neither account for the reliable correlation of the name-match variable with the auditory short-term memory-span score nor for the fact that the correlation of performance on the short-term memory task and effective reading speed disappears when the name-match variable is taken into account. Indeed, it appears that the processing ability tapped by the name-match task is not restricted uniquely to visual processing tasks.

A second possibility is that the name-match variable is tapping a general process involved in accessing information in long-term memory. However, memory access is also required in the listening comprehension task, and performance in the matching tasks was independent of performance in the listening comprehension task (excluding the synonym task). Thus, a general memory access interpretation seems inappropriate. However, a more specific memory access interpretation specifically involving accessing letter-identity information seems to be a viable possibility. Perhaps faster readers, like "high verbal" individuals, simply have swifter access to letter codes stored in long-term memory (Hunt et al., 1975).

Certainly, the regression analyses and partial correlations show that the one task that most clearly requires access to letter codes, the name-match task, is measuring a processing difference between fast and average readers that is not so clearly reflected in the other reaction-time scores. But can this interpretation account for the pattern of differences between fast and average readers in the other tasks? The letter-code access hypothesis is compatible with the lack of any relationship between the reaction-time variables and listening comprehension, since letters are not involved in the listening comprehension task. However, letters were used in the auditory short-term memory task; and consistent with the view that accessing long-term memory codes facilitates immediate recall, the small fast-reader advantage in this task can be attributed to faster access to letter codes.

As far as the other reaction-time tasks are concerned, the question arises, Can letter-code access be the sole determiner of reaction-time differences between readers even though we found faster reaction times for faster readers on all of our reaction-time tasks? The simple pattern-match task does not require letter-code access, and faster readers showed a small but reliable advantage in reaction time over slower readers. However, our analysis of the error rates suggest that this difference may be largely attributable to a speed–accuracy trade-off; faster readers had faster reaction times, but at the same time, they had lower accuracy.

Faster readers also had faster reaction times in the letter-matching task when the pair of letters was physically identical. On these trials, a correct response could be made on the basis of the physical characteristics of the pair alone, without necessarily encoding the letters. However, we can explain the difference obtained on these trials in terms of the letter-access hypothesis if we assume that the comparison process makes partial use of letter-identity information. A very simple model of the processing involved in comparing physically identical letter pairs can be constructed based on the joint use of both visual-code and letter-code information. In such a model, visual-code information accumulates at a faster rate than letter-code information (accounting for the shorter mean reaction time for the physical-same pairs), but the comparison process receives some information from the slower identity encoding process as well. If so, the time required for the accumulation of enough total information for a decision would be somewhat faster for subjects who accessed letter codes faster. This model seems particularly applicable in our letter-match task, since subjects were required to respond on the basis of name information on a majority of the trials. (Name information was necessary for name-same responses and for different responses.) This situation may well encourage partial reliance on letter information even on trials for which physical information would be logically sufficient for correct responding.

The correlation and regression analyses suggest that the synonym-match variable is tapping two component processes that are important determiners of reading ability. One component appears to be knowledge and/or use of word meanings, as indicated by the high correlation of the synonym reaction-time variable with the SCAT Verbal score and with listening comprehension. The other component, which is picked up by the name-match variable, can be accounted for by letter-code access. If, as many authors suggest, letter identification is indeed a component of fluent word identification (Estes, 1975; Gough, 1972; McClelland, 1976), then faster access to letter codes might be a particularly potent source of individual differences in the synonym task, as well as in reading, somewhat independently of the process of accessing semantic codes for particular words (LaBerge & Samuels, 1974).

For the same reasons we gave above for the synonym task, faster letter-code access should give faster readers a reaction-time advantage in the homonym task as well. The relationship between reaction time on the homonym task and reading ability is totally accounted for by the name-match variable. The fact that the homonym variable had a relatively low correlation with reading speed suggests that whatever other process comes into play in comparing the pronunciation of two words (such as phonological encoding processes) have little to do with individual differences in the ability to read effectively for meaning. However, this conclusion is clouded by the accuracy differences found in this task, which is discussed further later.

The multiple-display task also shows small overall differences correlated with individual differences in reading ability, although there is some possibility of contamination by individual differences in accuracy criterion. In any case, the letter-code access hypothesis permits us to account for the reaction-time differences obtained in this task if we add three reasonable assumptions: (a) The task is performed by a serial, self-terminating comparison of letter identity codes. (b) Identity codes for display characters are accessed in parallel or at least at a faster rate than they can be compared to the target. (c) The rate of comparison of codes is equivalent for the two groups of readers. The first assumption in conjunction with the letter-code hypothesis implies that the name code for at least one letter will become available sooner for fast readers than for slow readers so that the comparison process can begin sooner. The second assumption implies that after the first letter is encoded, rate of comparison rather than the rate of encoding additional letters will determine when the subject will finish comparing. The third assumption together with the second implies that the increase in reaction time as a function of display size will be equal for both groups. Together, then, these assumptions account for the fast reader advantage and its independence of display size. In addition, the assumption that the multiple-display task is performed by comparing letter codes is consistent with the fact that the difference between fast and slow readers in this task is nearly identical to the difference obtained on the name-match trials of the letter-match task.

Our failure to find any reliable difference in the search rates of fast and average readers in the multiple-display task is consistent with other investigations of visual search times for younger readers. Leslie and Calfee (1971) found no differences in the search or comparison rates of normal and retarded grade school readers when the displays and target items were words. Katz and Wicklund (1971, 1972) compared second- and sixth-grade readers on their abilities to search short lists of words or letters for target items. Again, they found no differences related to reading ability in their subjects' search rates over increasing display sizes.

Although we found an overall difference in reaction times for fast and average readers, only one of the previously mentioned studies found such a speed advantage for better grade school readers. Katz and Wicklund (1971) found that when the display items were words, better readers had a constant reaction-time advantage for deciding whether the target word was present or absent in the display list, independent of the display size. However, Leslie and Calfee (1971) reported no overall reaction-time advantage for their normal readers compared to their retarded readers. Also, Katz and Wicklund (1972) found no overall reaction-time advantage for better readers when the target displays were lists of unrelated letters. Thus, these reaction-time studies are somewhat inconclusive as far as determining whether better readers of grade school age have the same sort of reaction-time advantage over slower readers that we found with our older readers. Perhaps at the levels of proficiency of the younger readers, individual differences in letter-code access have not yet developed, and differences in reading ability at these early ages are the result of other factors.

The letter-code access hypothesis appears to provide an acceptable account of our reaction-time differences and is consistent with our correlation and regression results. Nevertheless, the overall pattern of divergent reaction times for fast and average readers warrants further consideration of the possibility that fast readers have an advantage in the speed of forming representations of visual stimuli independent of memory access. The simple-match task does not appear to require letter-code access, so the (weak) relation between reaction time on this task and effective reading speed is compatible with the view that letter-code access is producing the reaction-time advantage for faster readers in our other tasks. However, the results of the simple-match task were somewhat ambiguous. Although the correlation of the simple-match variable and effective reading speed was nonsignificant when accuracy was controlled, this correction for a speed–accuracy trade-off may hide a true relation between speed of performance on this simple task and effective reading speed that could emerge in a retest with accuracy equated. However, simply repeating the simple-match task is inadequate for testing this hypothesis for other reasons. That the task produced very rapid reaction times and very low error rates would make interpretation of any failure to find a difference between fast and slow readers difficult. In line with the diverging trend, we would expect to find the smallest differences on the fastest tasks so that the absence of a difference would not be informative. Thus, to provide a clearer opportunity to discriminate between the letter-code hypothesis and the general visual processing speed hypothesis, we developed a new dot-pattern matching task. This task used very unfamiliar stimuli of sufficient complexity to produce reaction times longer than those produced by the name-match task. In Experiment 2, we compare reaction times for fast and average readers on this new dot-pattern matching task.

Accuracy in the Homonym Task

In addition to listening comprehension and name-match reaction time, accuracy on the homonym task accounted for a significant independent component of the variance in reading ability. Thus, it appears that knowledge of the sounds of printed words is a correlate of reading ability that is independent of general language comprehension and memory access skills.

The presence of this accuracy difference on the homonym task makes it difficult to reach a firm conclusion on the relationship between phonological encoding skills and reading ability. First, the accuracy differences on this task indicate that the reaction-time results may be rather distorted. Second, the use of actual homonyms, coupled with the apparent importance of knowledge of word meanings in this task, makes it clear that the task may not be tapping phonological encoding skills: subjects may simply be using knowledge of the sounds of the specific words rather than phonological encoding skills per se.

To address these points, Experiment 2 compared fast and average readers on a new homophone task. This task differed from the homonym task of Experiment 1 in that all the stimuli were pseudowords instead of familiar words. Since the stimuli are not actual words, knowledge of the pronunciations of individual words will not be of any use. If differences in knowledge of the sounds of specific words is what is responsible for the accuracy differences in the homonym task of Experiment 1, then we expect to find no systematic accuracy differences in the homophone task. This in turn will eliminate the difficulties of comparing the reaction times for the two groups. In addition, the use of pronounceable pseudoword homophones allows us to look for reaction-time differences in the phonological encoding of pseudowords independent of knowledge of the pronunciations of specific words.

Experiment 2

Experiment 2 compared fast and average readers on the dot-pattern matching task and the pseudoword homophone task already described, as well as the name-match task of Experiment 1. The name-match task differed from the version used in Experiment 1 in that no physical match trials were included in the experiment.

Method

Subjects were tested on the three reaction-time tasks in a single session lasting about 1 hr.

Subjects

The two groups of 12 fast and average readers from Experiment 1 were compared. Because of the time span between the two experiments, some of our original subjects were not available for further testing. Of the 24 subjects tested in Experiment 1, 2 subjects from the fast group and 3 subjects from the average group could not be tested. Therefore, new subjects, all sophomores satisfying the same requirements specified in Experiment 1 (see Subjects, Experiment 1), were tested for reading speed using the same long-passage and short-paragraph reading tests described earlier. The first 5 subjects whose performance placed them in one of the two groups were used.

Apparatus and Procedure

As in Experiment 1, the stimuli were presented on a computer-driven display screen and subjects' reaction times were recorded automatically. Subjects were seated approximately 90 cm from the display screen. A stimulus letter subtended approximately $.3° \times .4°$ and a dot pattern subtended about $.9° \times .9°$.

The procedure for each task was similar to the procedure used for the reaction-time tasks of Experiment 1, except that only one subject was tested at a time. Also, following each trial, the subject was given feedback as to the correct response by an "S" (for same) or "D" (for different), which was displayed for 500 msec, 200 msec after the response.

Letter task. The letter task was similar to the letter task used in Experiment 1, except that there were no trials on which the letters were physically the same. Each stimulus item was a pair of letters, generated from the same set of letters as before (A, B, D, E, R), with one uppercase letter and one lowercase letter in each pair. Of the 160 test pairs, 80 pairs were same (having the same name) and 80 pairs were different. The test trials were preceded by 30 practice trials.

Dot-pattern task. The stimuli for this task were pairs of dot patterns. Each dot pattern was generated by randomly filling two columns per row of a 4×4 matrix. Any patterns resembling a common (i.e., nameable) pattern, such as a letter or familiar geometric shape, were eliminated. Of the 80 test pairs, 40 were the same and 40 were different. The different pairs were formed by moving a dot one column over in one of the patterns relative to the other pattern. The moved dot occurred in each row of the matrix an equal number of times. Examples of a same pair and a different pair are shown in Figure 4. The 80 test trials were

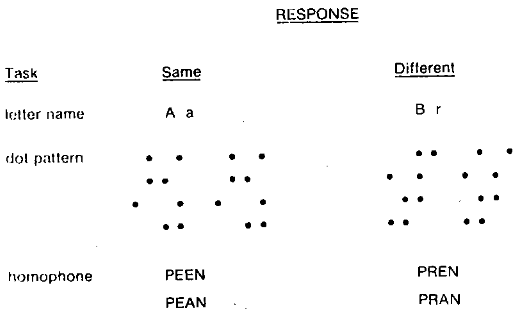

Figure 4. Examples of a same and different stimulus pair for each reaction time task used in Experiment 2.

preceded by 40 practice trials, with an equal number of same and different trials.

Pseudoword-homophone task. This task is the same as the homonym task of Experiment 1, except that the stimulus pairs were four-letter pronounceable pseudowords. The homophone test pairs were pretested for agreement as to pronunciation on a small sample of graduate and undergraduate students. For each pair of homophone pseudowords, a matched nonhomophone pair was formed by changing one or, at most, two of the letters common to each pseudoword in the homophone pair. This procedure ensures that the pseudowords in both same and different pairs were equally similar in terms of the letters they contained. Examples of a same and different pair are shown in Figure 4. Each subject was presented 30 practice pairs followed by 90 test pairs, half same and half different, in a fixed random order.

Results

The reaction times and error rates of the fast and average groups are shown in Table 8. As we found in the letter task of Experiment 1, fast readers had significantly faster reaction times for deciding whether the two letters have the same name, $F(1, 22) = 5.77$, $p < .025$. The size of the fast reader advantage for same and different responses, 78 msec, is a bit smaller than the 107-msec difference found in Experiment 1. Reaction times for different responses were longer than same response times, $F(1, 22) = 73.9$, $p < .001$, and there was no Response Type × Reading Speed Group interaction, $F(1, 22) < 1$.

Reaction times for the dot-pattern task were almost twice as long as those for the letter task, indicating that this task required considerably more processing. However, unlike the pattern of results from the name-match task, or from any of our previous reaction-time tasks, reaction times for the faster readers were not faster than reaction times for the average readers, $F(1, 22) < 1$. Overall, different responses were faster than same responses, $F(1, 22) = 13.9$, $p < .001$, but there was no Response Type × Reading Speed interactions $F(1, 22) < 1$.

For both tasks, there were no real differences in error rates for the two groups of readers. In the dot-pattern task, there was a correlation between reaction-time performance and accuracy as measured by d' ($r = -.71$, $p < .05$) suggesting a speed–accuracy tradeoff as a major source of differences in reaction time between subjects. However, neither reaction time nor accuracy were correlated with effective reading speed ($r = .10$ and $r = -.04$ with long-passage effective speed, respectively, $p > .10$; $r = .08$ and $r = .10$ with short-paragraph effective speed, respectively, $p > .10$). In the name-match task, there was no indication that fast readers had lower accuracy criteria than slow readers; the correlation of effective reading speed and accuracy was small and positive for both reading tests ($r = .30$ and $r = .33$ for the long-passage and short-paragraph scores, $p > .10$).

The reaction-time results of the pseudoword homophone task were very similar to the reaction-time results of the homonym task of Experiment 1. The fast reader group

Table 8
Mean Reaction Times and Error Rates for Tasks in Experiment 2

Task	Fast	Average	Difference
	Reaction times		
Letter	586	664	78
Dot pattern	1,256	1,230	−26
Homophone	1,221	1,365	144
	Error rates		t^a
Letter	6.0	6.8	−.64
Dot pattern	15.8	17.3	−.44
Homophone	23.0	24.3	−.38

[a] $df = 22$.

had a faster mean reaction time for deciding if the two pseudowords have the same sound, but the difference was not significant, $F(1, 22) = 1.82$, $p < .10$. Same responses were faster than different responses, $F(1, 22) = 32.5$, $p < .001$, and there was no Response Type × Reading Group interaction, $F(1, 22) < 1$. The error rates were high, as in Experiment 1, but there was no correlation of reading speed with accuracy ($r = .00$ and $r = .04$ for the respective reading speeds, $p > .10$) and no indication of a speed–accuracy tradeoff ($r = .26$, $p > .10$) where a negative correlation would indicate a speed–accuracy trade-off.

The correlation of name-match reaction time with homophone reaction time was .66, indicating that about half of the variance in the homophone reaction-time scores can be accounted for by the name-match reaction-time score. When we control for the name-match reaction-time score, the partial correlation of homophone reaction time with one measure of effective reading speed drops from .28 to −.07; with the other, it drops from .22 to .01. Thus, the small correlation between reaction time on the homophone task and effective reading speed is totally accounted for by the name-match variable. As in Experiment 1, the reliabilities of these reaction time variables were quite high ($r = .89$ for the dot pattern-match variable; $r = .96$ for the name letter-match variable; and $r = .97$ for the homophone-match variable). These results make it very difficult to argue that the small correlation between performance on the homophone task and effective reading speed is simply due to lack of precision in the measurement of those processing skills underlying performance in the homophone task.

Discussion

Since the reaction times for the dot-pattern task were as long as, or longer than, the reaction times for any of our other tasks and since we found no difference in reaction time for fast and average readers, we can rule out the possibility that the size of the reaction-time difference between fast and average readers is dependent solely on the amount of processing required by the task. Thus, the results of Experiment 2 are more consistent with the view that the fast reader advantage in the name-match task is due specifically to more efficient access to letter-code information in memory.

In Experiment 1, we found reliable differences between fast and average readers in accuracy on the homonym task. However, the pseudoword homophone task of Experiment 2 produced no difference in accuracy between fast and average readers. This result supports our earlier suggestion that the accuracy differences on the homonym task of Experiment 1 may have been due to individual differences in familiarity with specific words. However, there is another possible reason for the accuracy difference between the two homophone tasks that cannot be ruled out at this time. Fast readers may have more knowledge of complex context-dependent rules of phonological encoding than have slow readers (Calfee, Venezky, & Chapman, Note 2). Accurate phonological encoding of the pseudowords required only fairly simple correspondences (e.g., knowledge that c maps to /k/ before a, o, and u but maps to /s/ before i or e), whereas some of the word homophones involved subtler correspondences.

The results of the pseudoword homonym task provide no particular support for the view that individual differences in reading ability depend on phonological encoding processes per se. Although we found a large difference in mean reaction time between the reading groups in this task (and in the homonym task of Experiment 1), the difference was only marginally reliable. Even those differences that we did obtain can easily be attributed to letter-code access. Such an attribution might also be applied to the individual differences reported by Frederiksen (Note 3) in a vocal naming task. If, as suggested previously, a reader must first determine what letters are present in a string before translating it into a phonological code, faster access to letter-code information would allow phonological encoding processes to begin more quickly. No doubt there are large individual differences in the speed of phonological encoding, but they may not be related to individual differences in reading ability, over and above the relation of both phonological encoding and reading ability to letter-code access.

It appears then, in summary, that individual differences in letter-code access ability can account for the relationship between performance on several of our tasks and effective reading speed. This factor can also account for effects obtained by other investigators as well. For example, differences in letter-code access may account in part for the differences that we found on a number of tachistoscopic report tasks utilizing unrelated letter strings and sentences (Jackson & McClelland, 1975; see also Loiseau, 1974).

We have already noted that a fast reader advantage in accessing letter codes does not appear to be restricted to tasks utilizing visual presentation of letter strings. The results of our auditory letter-span task may be accounted for by superior access to letter codes in memory. This same observation applies to the findings of other experiments that have assessed the short-term memory characteristics of younger readers. Farnham-Diggory and Gregg (1975) compared fifth-grade readers, separated into groups of good and poor comprehenders, on both visual and auditory memory for sets of four sequentially presented letters. They found that better comprehenders had a small advantage in their ability to report all four letters correctly for both auditory and visual presentation. Similarly, Stanley (1975) reported differences between dyslexic and normal children on tests of short-term memory following both visual and auditory presentations of letter strings. Like our small effect in the auditory short-term memory task, these results may be due to more basic individual differences in the ability to access letter-code information in memory.

General Discussion

We feel that our results sound a necessary caution in the increasing use of the comparison of individual differences as an approach to understanding complex cognitive processes such as reading. The pattern of reaction-time differences between fast and average readers appears to indicate a basic processing difference not specific to one task. Any conclusion that we might have drawn from differences on just one of these tasks (e.g., the homonym task, to take the worst example), without the global picture spanning the range of tasks, would have been highly misleading. Furthermore, our results emphasize the difficulty of comparing the size of differences between tasks in an attempt to isolate specific processing abilities. Especially in the case of divergent interactions in conjunction with main effects, it is difficult to be sure that some pattern of task differences depends on the specific task demands of any particular task rather than on much more general demands imposed to differing degrees by them all. In our view, sources of individual differences in reading ability can be ascertained only by comparing fast and average readers on a variety of tasks and by designing tasks to pit some factors against others, as we were able to do in our comparison of readers on the dot-pattern and name-match tasks.

Our analysis seems to have found three rather independent correlates of individual differences in reading speed. One correlate lies within the domain of general language comprehension skills, as indicated by the strong relationship between performance on the listening comprehension task and effective reading speed. The second correlate lies within those processes involved in accessing letter-identity information. The third correlate is apparently related to knowledge either of the pronunciations of rare words or to the use of complex spelling-to-sound correspondences. What more can be said about these three correlates of reading ability? Are they mere by-products of reading practice or determiners of reading performance? Whether by-product or cause, what is the basis for the relationship of each correlate to reading ability? We consider each correlate in turn.

The ability to comprehend language is obviously causally related to effective reading speed. But what are the causes of these individual differences in comprehension ability? Perhaps this general comprehension component reflects differences in a general ability to access information in memory. It should be clear from our results and from the results of others (Perfetti & Lesgold, 1978) that memory access for word meanings is an important component of general language comprehension skill, independent of actual reading. Perfetti and Lesgold have also argued that verbal coding speed—the access and retrieval of a word name and its context-constrained semantic properties—is a major determiner of individual differences in discourse comprehension. Another potential component of general language comprehension may be the ability to maintain attention on the difficult task of comprehending over an extended period of time.

The differences between fast and average readers in accuracy on the homonym task could conceivably be a cause of individual differences in reading ability. However, there is no firm theoretical basis for postulating such a causal relationship. A number of studies suggest that phonological encoding processes are not involved in accessing the meaning of words (Baron, 1973; Frederiksen & Kroll, 1976; Kleiman, 1975); one can know the meaning of a printed word without knowing how to pronounce it. Further, we found no relation of speed of phonological encoding, over and above letter-code access, to effective reading speed. So, if speed of phonological encoding does not play a role in determining reading speed, and phonological encoding is not necessary for accessing the meaning of the words being read, it is unclear why accuracy in phonological encoding should affect reading speed. Thus, we prefer the view that the advantage fast readers have in accuracy on the homonym task is merely a by-product of the greater reading experience of the fast reader.

At first glance, determining whether faster letter-code access is a by-product or cause of more proficient reading seems to be a difficult task. Clearly, the speed of accessing letter codes in memory will be affected by practice reading. However, even if faster letter-code access is due to practice, it should also have an effect on reading ability. In fact, it is difficult to imagine how letter-code access could fail to be intimately involved in reading unless one believed that letter identification was totally bypassed in fluent reading (Smith, 1971). But, if letter identification were not part of the reading process, then we would not expect a correlation between speed of letter access and reading ability even as a by-product, since people who read more would not get more practice in letter identification. It seems more likely, then, that faster letter-code access is both a product of practice reading and a cause of individual differences in reading ability. There may be other causes of individual differences in letter-code access other than mere practice reading. Underlying letter-code access may be a general ability to access any memory codes from visual input (Morrison, Giordani, & Nagy, 1977). Also, the high correlation between name-match reaction time and the auditory short-term memory score suggests that the letter-code access skill picked up by the letter matching task may be partially independent of modality.

Assuming speed of letter-code access is a cause of individual differences in reading ability, it remains to be determined whether this component can be improved or manipulated independent of actual practice reading. Even if this component can be manipulated, there may be fixed characteristics of an individual's information-processing system that determine the asymptotic efficiency for accessing overlearned memory codes. If this is the case, attempts to train this component of individual differences in reading ability may yield little practical benefit.

Although it can hardly be a surprise that effective reading depends on both language comprehension and memory access for letter codes, it may be surprising that mature college student readers at a major state university have not all reached asymptotic levels of letter-code access ability. Surprising or not, our results do not support the views of some (e.g., Kolers, 1969; Smith,

1971) who have said that beyond the grade school level, individual differences in reading ability are only differences in comprehension ability. To be sure, language comprehension ability accounts for more of the variance in effective reading speed within our group of subjects than does letter-code access. However, we have demonstrated individual differences, among relatively mature readers, in a basic encoding process that is presumably a prerequisite for comprehension, and it will behoove us to pay some attention to differences in this specifically reading-related ability as well as comprehension skill.

Our results, in conjunction with the results of a recent series of studies reported by Perfetti and Lesgold (1978) underscore the importance of accessing memory information in reading. We must access information in memory before we can comprehend what we are reading. It is also worth noting that memory access may play a very important role in other aspects of the reading process, such as generation of expectations for subsequent input and guidance of eye movements. If the various components of the reading process are strongly interdependent (Rumelhart, 1978), then greater efficiency in any one component will influence all the others as well.

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